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Flow in double-porosity aquifers: Parameter estimation using an adaptive multiscale method

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ABSTRACT

The double porosity model (DPM) concept is a widely used approach to simulate flow in fractured aquifers. Parameter estimation methods to calibrate standard groundwater flow models have been rarely applied to the DPM. In this paper, we make use of a multiscale parameterization which defines the spatial distribution of parameter by an adaptive discretization refined within the iterative inversion procedure. The mathematical developments, including a presentation of the adjoint state equations, and the adaptive multiscale algorithm are described in detail. The parameter estimation procedure is applied to a heterogeneous synthetic case, where each type of parameter is spatially distributed according to a different variogram. Without any prior knowledge of theses variograms conditioning the adaptive multiscale method, the latter is able to retrieve with good precision the reference model for both its local parameter values and their associated spatial distribution.

1. Introduction

The quantification of flow in natural fractured reservoirs is an important issue for water resources and remains a very challenging topic. As for other groundwater reservoirs, monitoring water pressure heads and their evolution in time is a key to obtain data that can feed the inversion of a hydrodynamic model. In this study, it is dealt with the inversion of a flow model for fractured aquifers by focusing on two major questions. (1) How to develop an efficient inversion technique that can deal with an important number of hydrodynamic parameters because the aquifer is heterogeneous, and (2) how to propose a parameterization able to retrieve the heterogeneity of the aquifer while being parsimonious on the number of handled parameters?

The existing conceptual models for fractured reservoir representations can usually be sorted into two categories [1]: Discrete Fracture Models (DFM), where the fractures are treated explicitly, or continuum models, where fractures and matrix are represented by a single or several separate but overlapping interacting equivalent porous continua (EPC). Reference works on DFM can be found in [2–6], among others. The EPC approach is very popular because it requires a less detailed knowledge of the fracture network (geometry, density, etc.) than DFN [7,8]. Since the pioneering works of Barenblatt et al. [9], Warren and Root [10], Moench [11], Long et al. [12] and Neuman [13], the EPC approach has been extended to multiple continua representations within both deterministic and stochastic frameworks, e.g., [14,15]. Reviews and discussions can be found, for instance, in Berkowitz [1] and Neuman [16].

When applicable, the main drawback of EPC approaches is the definition of the equivalent hydrodynamic parameters (porosity and permeability) of each continuum and of the parameters ruling the fluxes exchanged between different continua at the scale of the grid cell. The deterministic estimation of these parameters relies upon the use of an adapted up-scaling technique [17]. However, depending on the fracture network characteristics (density, percolation threshold, characteristic lengths of the fractures compared with the size of the investigated domain, etc.), up-scaling local properties at the scale of the grid cell may be flawed. The stochastic framework then becomes an interesting alternative by considering ensemble averages of the domain properties [1,4,18]. Another alternative is the computation of the local equivalent properties using local discrete fracture networks, e.g., [5,19–21].

Among these various model conceptions, we focus our work on the saturated double porosity model (DPM) in which fluid flow following Darcy's law only occurs in fractures and in which the matrix is considered for its storage properties. Double porosity models are widely used for large-scale simulations and in engineering. The objective of this paper is to propose a methodology

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for parameter estimation based on an inverse approach. The main parameters used to describe flow in a double porosity system are the hydraulic conductivity (or transmissivity) of the fracture continuum, the specific storage capacity of both fractures and matrix and the exchange rate coefficient describing water transfer between both continua. It is expected that the level of heterogeneity is different between these parameters (e.g., different variances and correlation lengths for a stochastic parameterization) as well as the impact of the parameters on water head fluctuations due to various stresses (in the case of interference pumping tests, for example). It must be acknowledged that very few metrics based on systematic studies inform on how a heterogeneous DPM would behave regarding its main parameters. Only some partial sensitivity analysis exist in the ongoing literature, but they discuss simplified configurations such as homogeneous and fractal DPM, e.g., [22–24]. Though DPM models have been widely used and enhanced, especially in the domain of oil engineering, e.g., [25,26], surprisingly, the inversion of a DPM has not been abundantly addressed in the last decade, except in a few recent publications, such as Kaczmaryk and Delay [23,24], Le Goc et al. [27], Ray et al. [28], Fahs et al. [29] or Trottier et al. [30].

Kaczmaryk and Delay [23,24] inverted interference pumping tests performed at the experimental site in Poitiers, France. Their DPM model assumed symmetric radial flow in homogeneous and fractal media. In the latter, the hydrodynamic parameters followed power-scaling laws regarding the lag distance between pumped and observed wells. The authors also added a hyperbolic wave propagation to account for the very rapid propagation of pressure depletions in karstic conduits. Le Goc et al. [27] proposed a hierarchical identification method relying on steady-state flow data and geometric information to estimate both the hydraulic properties and the hydraulic structures of channels embedded in a significantly less permeable medium. Ray et al. [28] reconstructed binary media (some kind of DPM) by inverting a Karhunen–Loève expansion of the covariance of the proportions of binary facies (highly permeable versus weakly permeable). The inversion of the Karhunen–Loève expansion resorted on an adaptive Markov Chain Monte Carlo. The parameter estimation approach in Fahs et al. [29] used a parameterization based on a zonation technique, and the inversion algorithm allowed for the identification of both the parameters assumed constant per zone and the geometry of the zones. Finally, Trottier et al. [30] applied an inverse procedure based on a multiscale parameterization to interpret interference pumping tests from the experimental site in Poitiers, France.

This multiscale parameterization had already been applied to inverting a single continuum at the local (site) scale [31] as well as at the regional scale [32]. It offers the advantage of discriminating the subareas of a modeled domain that need to be highly parameterized, while others necessitate a few parameters. Differences in the local size of the parameterization can be the consequence of user-defined constraints or the consequence of the inverse problem itself. In the latter case, the number of spatially distributed parameters is automatically increased in subareas where the model does not fit data very well or in subareas where the convergence of the inverse problem is not optimal. The theoretical bases of the parameterization were never described in detail. Therefore, all mathematical derivations applied to transient DPM are properly presented in this paper.

In the framework of descent methods for inverse problems, there is no rule grounded in rigorous metrics stating whether a sensitivity-based algorithm is better than a method approximating the gradient components of the objective function. On the one hand, a sensitivity-based method (e.g., a Levenberg–Marquardt algorithm) generates sharp descent directions in the parameter space when the model sensitivities to parameters are calculated by a direct differentiation of the forward problem. Nonetheless, each iteration of convergence requires solving as much forward problems (sensitivity calculations) as the number of sought parameters. On the other hand, gradients approximations based for instance on the so-called adjoint state calculation are less demanding. Irrespective the number of sought parameters, calculating the adjoint state requires the resolution of a single problem (two for flow in a DPM, see hereafter) very similar in its form and computation needs to the forward problem. The downside is that only the gradient components of the objective function are calculated; the sensitivities are unavailable with the consequence of a poor evaluation of the uncertainty on parameters and their cross-correlation. In addition, Quasi-Newton algorithms seeking descent directions in the parameter space only on the basis of gradient components may be inaccurate and require many iterations of convergence. As a rule of thumb, Quasi-Newton algorithms never need more than fifty times the number of iterations used in the sensitivity-based methods. This makes the adjoint-state technique well-suited to highly-parameterized problems. Because the multiscale parameterization discussed hereafter can manipulate a large number of parameters, the automatic inversion of a DPM will be handled by means of a gradient-based method using the adjoint state equations. Given the approximations concealed in these methods, it is important that the adjoint state equations are developed rigorously to obtain precise trajectories.

The work is presented as follows: Section 2 addresses the mathematical model used to simulate saturated flow in a DPM; the details of the parameter estimation procedure are described in Section 3; and finally, a numerical test inverting a complex synthetic flow scenario is proposed in Section 4.

2. Mathematical model

Many inversion exercises performed at the scale of regional aquifers rely on data in the form of hydraulic heads corresponding to water pressures plus local elevation averaged over the screened portion of monitored wells. Generally, these data barely discriminate the vertical components of flow, which makes researchers assume that the flow is two-dimensional and mainly horizontal (the so-called Dupuit assumption). It is obvious that a two-dimensional approach is a priori not appropriate when the vertical component of flow is non-negligible, for example in the presence of channeled flow in sub-horizontal layers connected by opened vertical fractures. But in this case, it is likely that the continuous approach to fractured reservoirs would not be suited too. Recently, Trottier et al. [30] used a dual continuum in a two-dimensional model to invert interference data from a karstic limestone aquifer. There exist vertical components of flow in this aquifer as evidenced by Chatelier et al. [33]. But at the scale of the aquifer, these vertical components are evenly distributed and homogenize fairly well. The two-dimensional approach becomes applicable provided one is not interested in identifying the local properties of a specific set of fractures.

On a technical standpoint, there is no special difficulty in extending the approach discussed below to three-dimensional flow. Both the multiscale parameterization and the adjoint state formulas would remain similar. A three-dimensional approach would only complicate the numerical implementation by manipulating discretized blocks (for the forward problem and the parameterization) instead of planar grids. However, a key question, beyond the scope of the present study, is to know which data provide valuable information to condition accurately three-dimensional flow at the scale of the aquifer. As told above, we doubt that classical head measurements are relevant, and additional information is needed. Incidentally, one should also know how to bridge this information with a flow model.